Field measurements of evapotranspiration rates on seven pervious concrete pavement systems

Mesures in situ de l'évapotranspiration de sept systèmes de revêtements en béton poreux

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RÉSUMÉ

Les systèmes de revêtement en béton poreux présentent une certaine capacité de rétention d'eau pour les eaux pluviales et en conséquence un taux d'évapotranspiration supérieur au système de revêtement imperméable. Au cours de la période d'essai d'août 2008 à novembre 2011 un total de 336 taux d'évapotranspiration quotidiens réels ont été mesurés sur un champ d'essai à Coesfeld, en Allemagne, en climat océanique modéré et en climat semi-humide avec un taux de précipitations annuel moyen de 843 mm/a, en utilisant la jauge d'évaporation-tunnel. Le taux d'évapotranspiration d'un système de revêtement imperméable est de 62 mm/a (7 % du taux de précipitations annuel). Un système de revêtement en béton perméable gris présente un taux d'évapotranspiration de 88 mm/a (10 %) et un système de revêtement en béton Fe_3O_4 de couleur anthracite présente un taux d'évapotranspiration de 105 mm/a (12 %). Le système de revêtement en béton perméable optimisé pour l'évaporation, ainsi que deux systèmes « rainures et pierres » avec différentes pièces de joint, présentent un taux d'évapotranspiration de 149 mm/a (18 %), soit 2,4 fois supérieur au système de revêtement imperméable. Le revêtement enherbé présente une évapotranspiration de 545 mm/a (65 %), presque neuf fois plus élevée que les systèmes de revêtement imperméables. Ces résultats pourraient trouver une application dans le coefficient de ruissellement des surfaces partiellement étanches en zone urbaine.

ABSTRACT

Pervious concrete pavement systems have a certain water retention capacity for rainwater and therefore a higher evapotranspiration rate compared to an impervious pavement system. Over the test period from August 2008 to November 2011 a total of 336 actual daily evapotranspiration rates were measured in a test field situated in Coesfeld, Germany, under a moderate oceanic and semi-humid climate with an average annual precipitation rate of 843 mm/a using the tunnel-evaporation gauge. The evapotranspiration rate of an impervious pavement system is 62 mm/a (7 % of the annual precipitation rate). A grey pervious concrete pavement system shows 88 mm/a evapotranspiration rate (10 %) and a Fe_3O_4 coloured anthracite pervious concrete pavements system shows 105 mm/a evapotranspiration rate (12 %). The evaporation-optimized pervious concrete pavement system, as well as two groove-and-stone-systems with various seam parts, have a 2.4 times higher evapotranspiration rate of 149 mm/a (18 %) compared to the impervious pavement system. The grass paver has a nearly nine fold higher evapotranspiration of 545 mm/a (65 %) compared to impervious pavement systems. These results could find application in the run-off coefficient of part-sealed surfaces in urban areas.

KEYWORDS

Evapotranspiration, Pervious concrete, Water-permeable pavements

1 INTRODUCTION

Pervious pavement (PP) can help to limit, mitigate or compensate soil sealing in urban areas (SWD 2012) and has played an important role regarding with the attenuation of runoff peak flow (Rushton 2001), avoiding flooding risks (Gomez-Ullate et al. 2011a), and the reduction of pollutants (Coupe et al. 2003; Fernandez-Barrera et al. 2011). PP provide other important advantages, such as recharge of aquifers (Ferguson 2011), erosion control (Wright 2008) and growth of urban amenity (Ellis et al. 2004). PP has been widely adopted last 20 years, especially in car parks (Sañudo-Fontaneda et al. 2013). A lot of field researches have been carried out in car parks all over the world such as Collins et al. (2008) in the USA, Pratt et al. (1995) in the UK, Dierkes et al. (2002) in Germany, Lucke and Beecham (2011) in Australia, Pagotto et al. (2000) in France, Acioli et al. (2005) in Brazil and Gomez-Ullate et al. (2011b) in Spain, amongst others. The evapotranspiration rates have been, up to now, neglected in spite of playing an important role in the urban water balance.

Regarding to nation-wide German requirements 30 % evaporation, 0 % infiltration and 70 % surface run-off have been assumed for impervious pavement systems (Sieker et al. 2009) with a run-off coefficient of 0,5 to 0,75 (i.e. 50 to 75 % of precipitation, DWA 2007). Water-permeable pavements indicate 8 % evaporation, 80 % infiltration and 12 % surface run-off (Sieker et al. 2009) with a run-off coefficient of 0,25. Grass paver indicates an evapotranspiration of 40 % of the annual precipitation (Wessolek 2001) and a run-off coefficient of 0,13. There is a tremendous difference between the EU wide run-off requirements of 0,5 to 0,6 for permeable pavers and 0,6 to 0,7 for concrete grass grids (SWD 2012).

Since 2007 new pervious concrete pavement systems (PCPS) were developed within a research project funded by the German Federal Environmental Foundation (Az. 23277-23). The objective of this research project was to increase the evapotranspiration rates of pavement systems and to reduce the run-off rates of sealed surfaces in urban areas. The objective of this paper is to present the final results of the overall field measurements.

Figure 1: Field test area with tunnel-evaporation gauge (TUV).

In the first field measurement Starke et al. (2010, 2011a) measured the actual evapotranspiration rates of different urban surface types using the tunnel-evaporation gauge (TUV) by Werner (2000). The deeper loose layers of the street construction body (especially the sub-base) were disregarded because they have no significant influence on the evapotranspiration rate (Starke 2011a). The nature of the paving stone, as well as the seam and the seam-filling material, influences mainly the evapotranspiration processes. Pavement systems consisting of grey pervious concrete paving stones have a 16 % higher evaporation rate than pavement systems with impervious paving stones of the same colour (Starke et al. 2010). By a change in the paving stone colour (i.e. grey to anthracite) a further 19 % increase in the evaporation rate was observed (Starke et al. 2011a).

In the laboratory Starke et al. (2011b) measured the evaporation rate of 29 different urban surface materials using a newly developed laboratory evaporation measuring device (LEMD). The main focus was placed on PCPS. By changing the concrete recipe a further increase in the evaporation rate was possible (Starke et al., 2011b). Two-layered pervious material with a fine grained top layer and a coarse bottom layer showed the highest laboratory evaporation rates (Starke et al. 2011b). However, Starke et al. (2011b) could not clarify which parameters are crucial for high evaporation rates; aside from hydraulic parameters further soil physical parameters could also be responsible. From these laboratory results a pre-selection of paving stones with anticipated higher evaporation rates for the second field measurement is possible.

2 INVESTIGATION AREA

The test field, which was built in Coesfeld about 40 km west of Münster in Germany in 2007, consists of seven hexagonal areas (Figure 1). The pavements are built with no slope. All areas are divided from the others by plastic ‘walls’ that extend from 1 cm above the paving stone surface to the bottom of the sub-base (620 mm below the surface) (Starke et al 2011a). A lateral flow of infiltrated water between any two areas is prevented, as is any surface runoff (Starke et al 2010). The central reference area (Area 2.1) is constructed in accordance with the approved national technical specification for Germany (DIBT 2006). All pavement systems consist of the paving stone with a seam filling directly at the surface, below which is a base and a sub-base laid on the natural ground. All general information on the materials used is shown in Table 2.

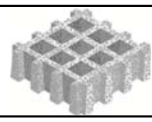
The climate in Coesfeld can be described as moderate oceanic and semi-humid with dominating westerly winds. The average annual long-time amount of precipitation in Coesfeld is about 843 mm/a (1961-1990). In cold months (December – February) the precipitation rate is 218 mm and in warm months (March – November) the precipitation rate is 625 mm/a. The annual mean temperature is 9.5°C - 10°.

3 MATERIALS

Seven different concrete pavement systems were selected for further measurements in the test field. The characteristics of these pavement systems and the test fields on Area 1, Area 2.1, Area 2.2 and Area 4 have been already described by Starke et al. (2010, 2011a). Because of the changed area numeration Area 1 is now termed Area 2.6 in Starke et al. (2010), Area 2.2 becomes Area 2.3 in Starke et al. (2011a) and Area 4 is now Area 2.7 in Starke et al. (2011a); Area 2.1 has the same numeration in all publications. All detailed information on the different pavement systems and the test field areas are summarised in the following Table 1 and 2.

The crucial factors for high evaporation rates are the characteristics of the internal surface of the paving stones. This is the final result of further laboratory soil physical research on 29 different surface materials (Starke et al. 2011b). The evaporation-optimized pervious concrete paving stone consists of a two-layered pervious material comprising a fine grained water-permeable top layer and a coarse grained water-permeable bottom layer. The fine grained top layer should be 20 mm thick with a very short roughness length. The ‘wettability’ could be enhanced by addition of iron oxides (such as Fe_3O_4) as dark pigments. Furthermore the use of cement CEM I could enhance the water retention capacity and could influence the thermal characteristics. Paving stones with an obvious difference between the thermal diffusivity at water-saturated and dry conditions (similar to high variation in heat conductivity) have a high evaporation rate. The paving stones of the pavement system in Area 2.3 (Table 1) show these effects quite clearly in the laboratory. This system was selected for further investigation in the second field measurement.

Table 1: Characteristics of the different pavement systems on the different test field areas.

Area / Properties	1	2.1 reference area	2.2	2.3	3.1	3.2	4
Material	impervious concrete	pervious concrete			groove-and-stone-system		chambered + pervious concrete
Icons							
Layers (top layer / bottom layer)	5 mm impervious	5 mm pervious	5 mm pervious	20 mm pervious	impervious	5 mm impervious	chambered + pervious
	impervious	pervious	pervious	pervious		pervious	
Grain material (top layer / bottom layer)	sand + basalt	quartz	quartz	quartz	sand + basalt	sand + granite	hard limestone
	hard limestone	hard limestone	hard limestone	hard limestone		sand + basalt chippings	
Grain shape (top layer / bottom layer)	rounded + crushed	rounded	rounded	rounded	rounded + crushed	rounded	crushed
	crushed	crushed	crushed	crushed		crushed	
Grain size (top layer / bottom layer)	0/3	1/2.2	1/2.2	1/2.2	0/3	0/3	0/5
	0/5	0/8	0/8	2/5		0/5	
Colour (top layer / bottom layer)	grey	grey	anthracite	anthracite	anthracite	anthracite	brown
			grey	grey		grey	
Cement	CEM II						CEM II + fly ash
Water/cement-value	0.31	0.35	0.35	0.31	0.31	0.35	0.21

Besides the internal surface structure of the paving stone, a variation in the seam-filling material has a high influence on evaporation. The high evaporation rates of natural soils could, in the laboratory, just be reached by the use of a special extensive substrata (Table 2). In the second field measurement two different groove-and-stone-systems are further investigated. The principal characteristic of Area 3.1 is the high part of the seams with about 8.2 % within an impervious pavement system, i.e. the widened grooves could act as water retention zones for the enhanced evapotranspiration from the seams. The characteristic of Area 3.2 is the impermeable top layer and a coarse grained water-permeable bottom layer; here the bottom layer could act as a water-retention source for the evapotranspiration from the seams. Further information about these two pavement systems and field areas is shown in Table 1 and Table 2.

Table 2: Characteristics of the test field areas.

	Properties \ Area	1	2.1 reference area	2.2	2.3	3.1	3.2	4
Paving stone	Material	impervious concrete	pervious concrete			perviuos groove-and-stone-system		pervious grass paver
	Colour	grey	grey	anthracite	anthracite	anthracite	anthracite	brown
	Size	200·100·80 mm	200·100·80 mm	200·100·80 mm	200·100·80 mm	210·140·80 mm	200·200·80 mm	250·250·80 mm
Seam	Material	1/3 basalt chippings	1/3 basalt chippings	1/3 basalt chippings	1/3 basalt chippings	40 % 1/3 basalt chippings + 50 % 0,5/1 washed sand	1/3 basalt chippings	30 % 1/3 basalt chippings + 70 % extensive substrata *
	Width	3-5 mm	3-5 mm	3-5 mm	3-5 mm	3-5 mm	3-5 mm	ca. 48·48 mm
Base	Material	2/5 hard limestone	2/5 hard limestone	2/5 hard limestone	2/5 hard limestone	30 % 2/5 hard limestone + 70 % 0,5/1 washed sand	2/5 hard limestone	70 % 1/3 basalt chippings + 30 % extensive substrata
	Thickness	30-50 mm	30-50 mm	30-50 mm	30-50 mm	30-50 mm	30-50 mm	30-50 mm
Sub-base	Material	0/32 hard limestone	0/32 hard limestone	0/32 hard limestone	0/32 hard limestone	0/32 hard limestone	0/32 hard limestone	0/32 hard limestone
	Thickness	500 mm	500 mm	500 mm	500 mm	500 mm	500 mm	500 mm
Total Pavement	Part of seams	5.7 %	5.7 %	5.7 %	5.7 %	8.2 %	3.9 %	ca. 55.3 %
	Installation	Jun 08	Jun 08	Jun 08	Sep 10	Sep 10	Sep 10	Jun 08 - Jun 10
	Gradient	0%						
	Infiltration rate (l/(s·ha))	920 new 43 with filled seems	1620	1200	1690	400	1600	950
	Disturbance	No disturbances from the sourrounding						
* filling in seam and chambers								

4 METHODS

Because of the hexagonal construction, the test field consists of six outer areas that surround the overall reference area. The hourly evapotranspiration rates (mm/h) are measured with a time resolution of 12 minutes (i.e. five measurements per hour) by a tunnel evapotranspiration measurement device (TUV, after WERNER 2000), further described in Starke et al. (2010). The TUV is placed between the two compared areas. By a lifting arm the measuring unit of the TUV is pivoted alternately on both pavement systems and depending on weather conditions, the TUV rotated at irregular intervals over the test field by hand. The daily evapotranspiration total (in mm/d) is calculated based on the 24 hourly evapotranspiration rates. Over the test period from August 2008 to November 2011 a total of 336 daily evapotranspiration rates were measured for this objective. For 70 % of the test period no values were collected due to phases of maintenance, sensor calibration, alterations of the pavement systems, power breakdown and frost-emergency switch-off (e.g. if air temperature ≤ 3°C and wind speed ≥ 8 m/s) or when further surface material was investigated (Starke et al. 2010, 2011a).

The evapotranspiration of the centered reference area was measured over almost all 336 test days. A relative comparison of the different pavement systems is only possible by the direct comparison of every outer area with the reference area in the centre.

Within a correlation analysis the daily evapotranspiration rates (mm/d) of two bordering areas could be directly compared over the number of test days. In Figure 1 a typical correlation analysis is shown. The general correlation coefficient r = 0,93 is very high; that means that the relationship between the central reference Area 2.1 and the outer Area 2.2 is nearly perfect.

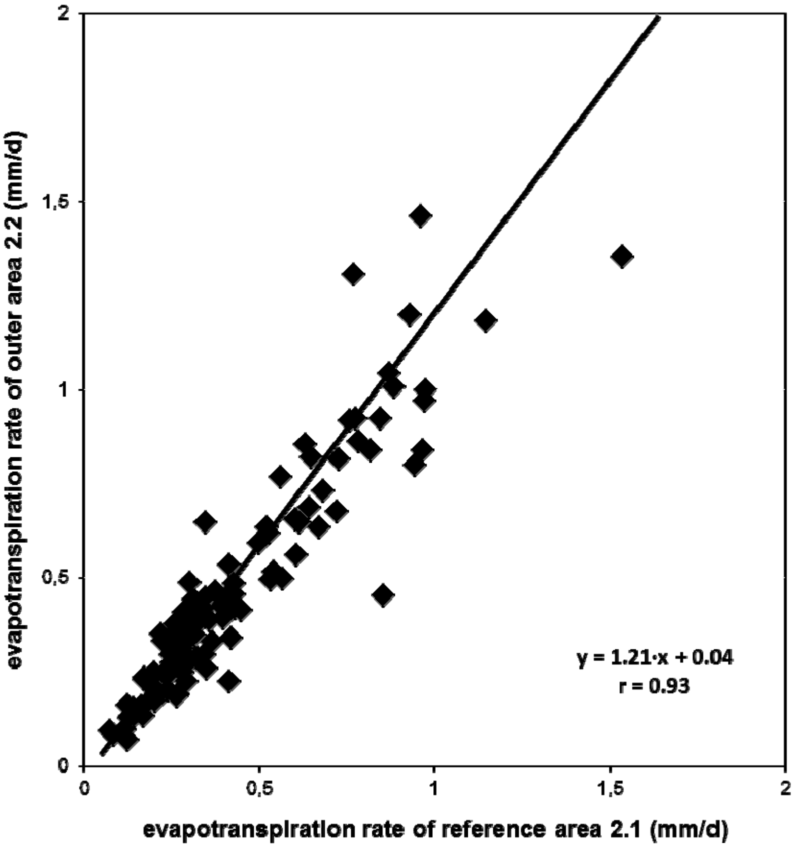


Figure 1: Typical correlation analysis of daily evapotranspiration rates between the reference Area 2.1 and the outer Area 2.2.

5 RESULTS AND DISCUSSION

The results of the correlation analysis (Figure 1 and Table 3) show the influence of the weather conditions. For this reason the conversion factors compared to the central reference area varies.

The results in the field measurement show that there is no correlation between the evaporation rates measured in the laboratory and the evapotranspiration rates measured in the field test area. The reason is primarily because the laboratory test reproduces just a small section of the natural conditions. In the laboratory, mainly the drying period was reproduced (Starke et al 2011b) and the groove-and-stone-systems could not yet be transferred to the laboratory. The evapotranspiration rate in the field test areas varies for different impervious and PCPS. The variation of the colour (from grey to anthracite) in Area 2.2 decreases the albedo and results in a 1.2 times higher evapotranspiration rate compared to the reference area. Compared to an impervious concrete pavement system the evapotranspiration is 1.4 times higher. Furthermore, the water retention capacity and 'wettability' of the internal fine grained surface of the top layer is increased. The thicker the fine grained top layer of the paving stones in Area 2.3 the greater the internal surface; this leads to a 1.7 times higher evapotranspiration rate compared to the reference area.

The seams also have a significant impact on the evapotranspiration rate. The bigger the seam the more vegetation (such as grass, moss and lichen) could grow and the correlation coefficient decreases with the increased seam size. A grass paver has a minimal correlation coefficient with the maximal vegetation degree and a 6.2 times higher evapotranspiration rate compared to the reference area.

The impervious concrete pavement system shows directly that after installation a 0.6 times lower evapotranspiration rate is achieved since the rainwater could directly infiltrate through the open seams into the water-permeable street subsurface. An old impervious concrete pavement system with artificial clogged seams has a 0.7 times lesser evapotranspiration rate. After rainfall much rainwater is standing on the paving stones without infiltration; during this short periods the evapotranspiration is greater compared to the reference area.

Table 3: Comparative evaluation of the final results.

Area / Properties	1	2.1 reference area	2.2	2.3	3.1	3.2	4
Material	impervious concrete	pervious concrete			groove-and-stone-system		grass paver
Laboratory evaporation rate (g/7,5h)	3.9 (No. 3 *)	9.2 (No. 28 *)	8.7 (No. 29 *)	14.5 (No. 25 *)	n.m.	4.9 (No. 6 *)	3.1 # (No. 12 *)
Number of test days	47	336	105	39	62	58	25
Correlation coefficient *r*	0.93 - 0.97	1.0	0.93	0.90 - 0.97	0.69 - 0.78	0.75 - 0.97	0.57
Conversion factor (to reference area)	0.7	1.0	1.2	(1.1 -) 1.7	(1.4 -) 1.7	1.1 (- 2.3)	6.2
Conversion factor (to area 1)	1.0	1.4	1.7	2.4			8.8
Evapotrans-piration rate (mm/a)	62	88	105	149			545
Evapotrans-piration rate (%)	7	10	12	18			65

*: from Starke et al 2011b; n.m.: not measurable; # measured as full block stone

The groove-and-stone-systems react in a similar manner to the impervious pavement system. Influenced by the rainfall the evapotranspiration rate of Area 3.2 is up to 2.3 times higher compared to the reference area. However, the correlation coefficient decreases in this period down to 0.75. In general the evapotranspiration rate of Areas 2.3, 3.1 and 3.2 is greater than the reference area. The groove-and-stone-system in Area 3.1 shows 1.4 times higher (i.e. spring-time) to 1.7 times higher (i.e. autumn) evapotranspiration rates with great variations (correlation coefficient are between 0.69 and 0.78). The groove-and-stone-system in Area 3.2 shows 1.1 times higher (i.e. early summer) evapotranspiration rates compared to the reference area. The PCPS on Area 2.3 shows 1.7 times higher evapotranspiration rates in the spring-time and at least 1.1 times higher rates in dry summer months; all data have nearly perfect relationships (i.e. correlation coefficient between 0.90 and 0.97).

6 CONCLUSIONS

Over the 336 day test period during 2008, 2009 and 2010 (i.e. the first field measurement) the cumulative total precipitation was 566 mm. This amount related to the period March to November where the measurement of the actual evapotranspiration was carried out. The cumulative evapotranspiration of the central reference area is 79 mm for the same period. This is, on average, equivalent to 14 % of the cumulative total precipitation. As a function of the weather conditions the evapotranspiration rate percentage of the precipitation for the reference area is between 7 % and 44 % for a single month.

In the cold months (i.e. December – February) evapotranspiration measurements were not possible; anyway the actual evapotranspiration was considered insignificant due to the generally low temperatures. The average long-time evapotranspiration rate of the reference area is 88 mm/a compared to the average long-time precipitation rate of 625 mm/a for the warmer months (i.e. March – November). Regarding the average long-time annual precipitation rate of 625 mm/a, the percentage of the average long-time evapotranspiration rate of 88 mm/a is 10 % per year (Table 3).

The annual evapotranspiration rate of the other pavement systems shows a high variation. An old impervious pavement with sealed seams, and under certain vegetation influence (i.e. Area 1), shows an evapotranspiration rate of 7 %. Under the use of the optimized pavement systems (Areas 2.3, 3.1, and 3.2) the evaporation rate could be increased to 18 %. Using a grass paver the evaporation rate increases up to 65 % due to grass acting as a natural and active evaporator.

By replacing an old impervious pavement with a pervious pavement with a high evapotranspiration rate, the evapotranspiration portion could be more than doubled (i.e. a factor of 2.4 - see Table 3).

Finally, the nation-wide German runoff coefficient values of 0,25 (i.e. 25 % of precipitation) for water-permeable pavement systems, and 0,15 (i.e. 15 % of precipitation) for grass pavers, are too high compared to the previous described results. The EU-wide values are far too high. Furthermore the evapotranspiration rate of impervious pavement systems of 30 % has been overestimated in Germany; the available results show only 7 % evapotranspiration rate. In contrast, the evapotranspiration rate of pervious pavement systems of 8 % has been underestimated in Germany. The distribution of the urban water budget parts of an evaporation-optimized PCPS should be 18 % evapotranspiration, 70 to 82 % infiltration (depending on the soil permeability) and 0 to 12 % surface run-off. The urban water budget of grass paver should divided in 65 % evapotranspiration, 35 % infiltration and 0 % surface run-off; this correlates with a run-off coefficient of 0,0 (i.e. 0 % of precipitation).

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